ARISE: The Next Generation Space VLBI Mission

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Abstract

We have defined an affordable advanced Space Very Long Baseline Interferometry (VLBI) mission named ARISE (Astronomical Radio Interferometry between Space and Earth). A large space radio telescope with high aperture efficiencies between 1.7 and 43 GHz would be employed to make observations simultaneously with arrays of ground radio telescopes. The primary scientific goals include high dynamic range mapping of core-dominated active galactic nuclei (AGN), imaging of weak radio cores in AGN on scales of 0.01 parsecs or less, direct measurement of distances to nearby galaxies using the orbital parallax of their H_2O masers, and imaging of radio stars in their quiescent states with resolution better than 0.1 AU. The key design requirement of ARISE is a much higher sensitivity than will be available for the VSOP and RadioAstron missions in the 1990s, with a fringe threshold of 10 mJy at frequencies up to 22 GHz, and 20 mJy at 43 GHz, on a baseline to a single 25-m telescope of the Very Long Baseline Array. Critical design parameters for the 1.7- to 22-GHz range include the following: (1) a 20–30-m space antenna with approximately 60% aperture efficiency; (2) system temperatures of 10–20 K; and (3) a data rate of 1-2 Gbit/s.

Introduction

Very Long Baseline Interferometry (VLBI) is an astronomical observing technique used to obtain very high resolution at radio frequencies.[1,2] Ground-based VLBI has been used for more than 25 years, since the pioneering experiments in the late 1960s.[3,4] The technique employs two or more widely separated radio telescopes, each having highly accurate (but independent) frequency standards, simultaneously observe the same radio source. Data from a large bandwidth (currently as high as 112 MHz) are digitized and recorded at the telescopes, then brought together for cross-correlation at a central processing facility. Data from each pair of telescopes samples the two-dimensional Fourier transform of the radio-source brightness distribution. The combination of a large number of antenna separations (baselines) and the Earth's rotation gives a relatively complete sampling, and leads to an accurate reconstruction of the source brightness distribution.

VLBI is the highest resolution technique currently used in astronomy, even though VLBI observations are made at wavelengths typically ranging from a few millimeters to about 20 cm, 4–5 orders of magnitude longer than optical wavelengths. For example, the resolution of a ground-based VLBI experiment at a standard frequency of 22 GHz (1.3 cm wavelength), with a maximum projected baseline of 10,000 km, is approximately 0.28 milliarcseconds, a factor of about 400 finer than the resolution achievable with the Hubble Space Telescope. Higher resolution can be obtained either by observing at a shorter wavelength or by placing a radio telescope in Earth orbit. For example, the highest resolution achieved from the ground has been obtained by using observations at 86 GHz (3-mm wavelength), with angular resolution as fine as 0.06 milliarcseconds.[5,6]

VLBI observations between ground and space elements at centimeter wavelengths can provide resolution similar to ground-based millimeter VLBI. However, they sample different properties of the radio sources. Compact radio sources emit radiation generated by nonthermal processes; this radiation often is characterized by its strength as a function of frequency. Longer wavelength observations are much more sensitive to the steep-spectrum (stronger at low frequencies) jets which are present in many compact extragalactic sources. Many of these sources are only poorly resolved with ground-based VLBI, independent of observing frequency (source sizes generally decrease at least as fast as the wavelength). Their structure can be seen only with space-ground baselines. In addition, spectral-line sources such as water masers emit at fixed frequencies; better resolution of these objects can only be achieved by going to space. Finally, a key property of the non-thermal emission process of compact radio sources is the source brightness temperature. The brightness-temperature sensitivity of an interferometer depends only on the physical baseline length and not the angular resolution, so brightness temperatures above about 10^{12} K can be measured directly only with a baseline longer than an Earth diameter.

Past and Near-Future Space VLBI Experiments

VLBI experiments involving both space and ground elements have additional stringent requirements compared to those of ground-only VLBI. Frequency stability comparable to that of a hydrogen maser must be accurately transferred to the spacecraft from the ground. Wide-band digital data acquired at a rate greater than 100 Mbit/s cannot be recorded aboard a spacecraft for a significant period of time, so the data from the orbiter must be transmitted to the ground in real time. Both of these facts require that the orbiting VLBI antenna be in contact with a ground tracking station in order to obtain data.

The first demonstrations of Space VLBI were performed with a 4.9-meter antenna aboard an existing Tracking and Data Relay Satellite System (TDRSS) spacecraft in geosynchronous orbit.[7,8] Between 1986 and 1988, several experiments were performed at frequencies of 2.3 GHz (13 cm wavelength) and 15 GHz (2 cm wavelength); radio telescopes in Japan and Australia were used as the ground-based interferometer elements. At 2.3 GHz, 23 of 24 sources were detected in spite of limited sensitivity.[9] At 15 GHz, the detection rate was lower, due to the very poor sensitivity of the space antenna. However, the observations demonstrated the feasibility of transferring the ground frequency standard to the spacecraft with sufficient spectral purity to enable coherent observations at the higher frequency.[10]

The success of the TDRSS demonstrations played an important role in the genesis of two dedicated Space VLBI missions that are scheduled for the late 1990s. The Japanese Institute of Space and Astronautical Science (ISAS) will launch the VSOP (VLBI Space Observatory Programme) spacecraft (also known as MUSES-B) in September 1996.[11,12] The spacecraft will consist of an 8-m radio telescope and receivers at 1.7, 4.8 and 22.2 GHz, together with the associated electronics to permit the sampling of 128 Mbit/s at these frequencies. It will be in an elliptical orbit with a perigee altitude of 1,000 km and an apogee altitude of approximately 22,000 km.

In the 1997-1998 time frame, the Russian Astro Space Center is scheduled to launch the RadioAstron spacecraft into an elliptical orbit having a perigee altitude of 4,000 km and an apogee altitude of 77,000 km.[11,14] RadioAstron also will be a dedicated Space VLBI mission, carrying a radio telescope with a diameter of 10 meters. The observing frequencies will be similar to those for VSOP, with the addition of a longer-wavelength band near 0.3 GHz, and the maximum data rate also will be 128 Mbit/s. This mission will be an exploratory mission that will investigate radio source structures and brightness temperatures on very long baselines, but the large gaps in aperture (or Fourier transform) plane coverage will not allow imaging with good dynamic range possible with VSOP.

Extensive arrays of ground-based radio telescopes must observe radio sources simultaneously with VSOP and RadioAstron in order to provide the aperture plane coverage necessary for high-quality measurements of source brightness distributions. Among the participating ground telescope arrays are the U.S. Very Long Baseline Array (VLBA), the European VLBI Network (EVN), and the Australia Telescope National Facility (ATNF), as well as a number of other telescopes more loosely affiliated with these arrays.

Scientific Goals of ARISE

VSOP and RadioAstron will be the first "experiments" in Space VLBI that involve the use of spacecraft dedicated to making VLBI observations. However, due to the small space antennas and their high system temperatures (50-100 K at 1.7 GHz, 120-200 K at 22 GHz), the missions will have rather limited sensitivity; all calculations below are for a baseline to a single 25-m antenna of the VLBA.[15] At an observing frequency of 5 GHz, the 7σ detection threshold for VSOP will be approximately 110 mJy, while that for Radio Astron will be about 60 mJy (1 mJy = 10^{-29} W m^{-2} Hz^{-1}). At 22 GHz, the systems are much less sensitive, with detection thresholds near 400 mJy for both VSOP and RadioAstron. These sensitivities imply that only sources having flux densities on the order of 0.5 Jy (1 Jy = 1000 mJy) in a very compact core, can be observed with high dynamic range, and that objects with core flux densities less than 100 mJy cannot be detected. VSOP and RadioAstron therefore will be constrained to observe the brightest compact sources in the sky.

An obvious successor to VSOP and RadioAstron would be a mission with such high sensitivity that it could observe and detect sources with weak radio corm, including objects such as Seyfert galaxies, radio stars, extragalactic water masers, and lobe-dominated radio galaxies. ARISE would be such a mission. It would operate at frequencies between 1.7 and 43 GHz with very high sensitivity. The nominal 7σ detection threshold on a baseline to a VLBA antenna would be 2-4 mJy at 1.7 and 5 GHz, approximately 10 mJy at 22 GHz, and 20 mJy at 43 GHz; even weaker sources could be studied at the lower frequencies using phase referencing techniques. The enhanced sensitivity of ARISE, dual polarization feeds and receivers, plus orbit determination with an accuracy of tens of centimeters or less, will open up new areas of scientific investigation that are not possible with VSOP or Radio Astron. The new scientific goals, some of which are listed in Table 1, also cannot be achieved with ground-based VLBI because of the limited baseline lengths available on the Earth. These goals are similar to some listed for previously proposed (but unfunded) concepts such as the International VLBI Satellite (IVS) and QUASAT except that the much greater sensitivity of ARISE enables substantial scientific return beyond that envisioned for QUASAT or IVS.[16,17]

Table 1. Some key science goals of ARISE.

- Very detailed imaging of large samples of active galactic nuclei (AGN) at higher resolution than for ground arrays in both total intensity and polarized emission
- Imaging of compact radio sources in nearby weak AGN on scales smaller than the broad-line region (e.g., < 0.01 pc at 22 GHz for Seyfert galaxies at distances of 20-100 Mpc)
- Direct distance measurements of galaxies out to about 6 Mpc, using orbital parallaxes of H_2O masers
- Extremely sensitive phase-referenced imaging of radio stars in their quiescent states, with 5-GHz resolution of ().04 AU at a distance of 100 pc

Very high sensitivity is needed in order to study a large sample of AGN selected on the basis of apparently isotropic properties rather than the strength of their compact radio emission. We estimate that between 200 and 1000 AGN potentially can be detected using VSOP and RadioAstron, whereas more than 100).OO AGN could be detected using ARISE. For nearby AGN such as Seyfert galaxies, centimeter-wavelength observations from space are the only technique capable of both detecting and resolving weak core emission (typically a few millijansky) on the scale of the broad-line region (0.1 pc or less). In the subsections below, we give more details of the scientific goals of ARISE. Design of the spacecraft that would accomplish these goals is described following the discussion of the science goats.

Core-Dominated AGN

Core-dominated active galactic nuclei (AGN) will be the primary targets of VSOP and RadioAstron; these missions will identify the strong sources which can be observed with the greatest benefit by ARISE. Such objects have been observed extensively with ground-based VLBI, both in general surveys and in detailed studies of particular objects.[18-20] Rapid variability, with expansion of the radio jets with apparently superluminal speeds (i. e., apparently faster than the velocity of light, due to relativistic Doppler effects), are characteristic of the radio cores of these sources. A key question presently under investigation is the path taken by the discrete components in the jets as they move outward from the core, which has important implications for the underlying physical phenomena. The ARISE mission will provide the capability of viewing such components very close to the core after ejection; for a 20,000-km baseline at 43 GHz, a component ejected at an apparent speed of $10c$ (i. e., 10 times the speed of light) in a quasar at a redshift $z = 0.5$ will be a beamwidth from the core in less than a month after its ejection. As components move outward from the core, they overlap other components and also fade into invisibility because of expansion and energy loss by the radio-emitting electrons. The space-ground resolution of ARISE will be critical for keeping the components separated from one another, while the enhanced sensitivity will enable them to be monitored at a much greater distance from the core than will be possible with VSOP and RadioAstron.

Ground-based VLBI polarimetry has provided a wealth of information in recent years, often separating nearly unpolarized corm from highly polarized jets, when the two cannot be resolved in total intensity maps.[21] The magnetic field properties immediately surrounding the core are likely to be intimately related to the mechanism causing curvature in the]arscc-scale radio jets. However, at the limited resolution of ground-based VLBI, it is likely that the polarization is often masked by overlapping features within a single resolution element. Since the highest polarized flux densities in compact sources usually are much less than 100 mJy, VSOP and RadioAstron will be capable of only very limited polarization studies, predominantly at 5 GHz. The increased resolution and sensitivity of the ARISE mission, particularly at 22 GHz, will be ideal for separating the different polarized features and studying the physics of the region immediately surrounding the core.

For an 8-hour integration at 22 GHz, the minimum map noise for the ground-space baselines between VSOP and the VLBA will be about 1.5 mJy, implying a maximum achievable dynamic range (peak brightness/noise) of about GO() for a bright core-dominated source (the dynamic range of RadioAstron maps will be limited by aperture-plane coverage at a lower value). Assuming that a map noise three times the theoretically possible value is achieved, the dynamic range will be limited to roughly 200 to 1 in most sources. In contrast) ARISE will have about 50 times the sensitivity of VSOP at 22 GHz. Therefore, it would be theoretically possible to achieve a dynamic range of over 30,000 to 1 in the same source with a 1-Jy core. The actual value achieved will depend critically on the choice of orbit for ARISE. An orbit optimized for high-quality imaging would have an apogee altitude near 15,000 km, while a higher orbit would yield superior angular resolution at the expense of image quality. aperture-plane coverage of the final orbit and the quality of the calibration data for ARISE.

AGN with weak cores

Initial ground-based VLBI surveys of AGN concentrated on core-dominated sources because of the limited sensitivity available. However, statistical studies of such source samples are subject to extreme selection effects, because the relativistic jets in the core-dominated sources are pointing almost directly at the Earth. In the last few years, attempts have been made to make ground-based VLBI maps of sources whose emission is dominated by their large-scale (arcseconds or larger) radio lobes, and which therefore are selected based on an intrinsic property rather than because of a particular geometric relationship to us.[22] These studies have revealed properties that the lobe- and core-dominated sources have in common (e.g., parsec-scale jets pointing in the same direction as kiloparsec-scale jets) and some important differences (the lobe-dominated sources have much lower apparent transverse velocities).

Ground-space VLBI of radio-loud AGN with weak cores is not possible with VSOP and RadioAstron, because the cores are too weak to be detected. Therefore, ARISE is needed to elucidate both the polarization and total intensity properties of the innermost cores of lobe-dominated radio sources. Studies of the inner jet morphologies should help reveal the opening angles of the cones within which relativistic beaming occurs, which in turn can be related to the physics of the accretion disks and torii thought to be present at the centers of the AGN. ARISE would also provide the capability to make statistical studies of the distribution of brightness temperatures from less than 10^{10} K to nearly 10^{13} K in unbiased samples of extragalactic radio sources.

In addition to the lobe-dominated radio sources, there are many other AGN for which only a very small fraction of the energy output occurs in the radio part of the spectrum. These classes of objects are too weak to be observed with VSOP and RadioAstron, but are potential targets for ARISE. For example, one can consider Seyfert galaxies, relatively nearby spiral galaxies with weak radio sources in their cores. About 30 Seyferts have unresolved cores stronger than 10 mJy at 5 GHz on subarcsecond scales.[23] Since the cores tend to have steep spectra, there is little hope that any Seyferts can be detected from the ground using VLBI observations at 86 GHz; again, only space observations will suffice to obtain the highest possible resolution. At typical distances of 20–200 Mpc, the linear resolution at 22 GHz on a 30,000 km baseline is between 0.01 and 0.1 pc, smaller than or comparable to the size of the broad line region. Thus, observations of Seyfert galaxies using ARISE have the potential for probing the physics within the dusty torus that exists in the centers of Seyfert galaxies. As an example, the linear resolution of less than 0.01 pc in the nearby prototypical Seyfert galaxy NGC 1068 would be more than 1000 times finer than the compelling images of the ionization cone observed with the Hubble Space Telescope.[24,25]

Distances to External Galaxies using Water Masers

Water masers, with spectral-line emission at 22 GHz, have been detected in a number of external galaxies.[26] These objects are of two types-interstellar masers in star-forming regions that take part in the general galactic rotation, and megamasers associated with starbursts in the nuclei of the galaxies. Measurement of the relative proper motion of the interstellar masers and the megamaser (or another reference point) in the nucleus of the external galaxy (so-called "orbital parallax") can provide a direct distance measurement by comparison of the angular velocity with the linear velocity derived from the galactic rotation curve. In order to derive distances with accuracies better than 5%, baseline lengths must be known to better than 10 cm. The first effort at ground-based VLBI measurements of proper motions of extragalactic water masers was reported recently.[26,27] One of the limitations of that study was the inadequate resolution of the ground-based measurements; the results could be improved dramatically by using a sensitive antenna in space. The enhanced angular resolution available with Space VLBI will enable separation of adjacent maser spots so that relative intensity variations between the spots are not confused with apparent angular motions. At a distance of 1 Mpc, a rotation speed of 200 km/s corresponds to an angular velocity of 42 μas/yr, almost half the beam size of 92 μas for a 22 GHz observation on a 30,000 km baseline, but only about 15% of the beam size for a ground-based measurement on a 10,000-km baseline.

VSOP and RadioAstron will have inadequate orbit-determination accuracy (about 30100 meters, three orders of magnitude too poor) and inadequate sensitivity to make useful orbital parallax measurements. However, the proposed ARISE mission will be capable of measuring the orbital parallaxes of interstellar water masers to better than 5% in galaxies at distances of several Megaparsec, independent of the galaxy distance. At distances of 5 Mpc or more, thermal measurement error dominates and grows so rapidly with distance that the orbital parallax measurements will be limited to galaxies with distances of about G Mpc or less. (At present, interstellar masers have not been detected at distances greater than 3 Mpc.[26]) The geometric measurement of distances to several external galaxies by means of maser motions would have profound implications for cosmology, since it would bypass multiple indirect steps that are used to establish the current extragalactic distance scale.

Radio Stars

Radio stars are observed with VLBI techniques both for astrometric purposes such as tying radio and optical frames and for studying the physics of the stellar systems and their emission processes.[28] Stars emitting at radio frequencies typically are in binary systems. They usually are weak emitters, at the level of tens of millijansky or less, except during brief, unpredictable outbursts. Therefore, they will not be cletcc.table with VSOP or RadioAstron. Since the radio stars have steep spectra, they, like Seyfert galaxies, cannot be studied with ground-based VLBI at frequencies of 22 GHz and above. However, ARISE will provide the capability for sensitive observations of radio stars at 5 GHz, particularly if phase-referencing techniques can be used. Without phase referencing, the detection threshold on a baseline between ARISE and a VLBA antenna at 5 GHz will be 2-4 mJy, while phase-referencing techniques would enable source detection at a level well below 1 mJy. On a 20,000-km baseline, the linear resolution on a stellar system at a distance of 100 pc would be approximately 0.06 AU, only about 25 times the Earth-Moon distance. Thus the physics of stellar systems can be studied with very high sensitivity and unprecedented resolution using ARISE.

Other Investigations

A number of other scientific observations will be possible with ARISE.[17] The measurement of lens properties and time delays in gravitationally lensed extragalactic sources will enhance the modeling of such objects. Determination of the brightness distribution of H_2O megamasers in external galaxies will be useful for studying the physical characteristics of those sources, in addition to their role in the orbital parallax measurements described above. Measures of the structure or radio supernovae in the days immediately following their outburst also will be possible; such measurements will probe the nature of the particle acceleration process and the distribution of the matter surrounding the exploding star. Global reference frame unification at the milliarcsecond level also may be possible. Each of these investigations requires resolution better than that available on the ground, with sensitivity far better than that achievable with VSOP or RadioAstron.

ARISE Mission Concept

The ARISE (Advanced Radio Interferometry between Space and Earth) mission has been developed as the high sensitivity successor to VSOP and RadioAstron. A number of topics relating to the design of an advanced Space VLBI mission have been discussed in the Proceedings of an Astrotech 21 Workshop.[29] We have considered several possible mission concepts for such a mission, each representing a diverse set, of science objectives. The mission concepts proposed included a single 50-m space antenna operating at frequencies up to 5 GHz, and several 20-m orbiting telescopes operating simultaneously at frequencies of 90 GHz or higher. Analysis of the scientific potential of these missions led to the conclusion that any viable mission had to operate at a minimum frequency of 22 GHz. Since large, reliable, space-deployable antennas operating at 90 100 GHz would be prohibitively expensive, we have selected a concept for ARISE that is based on a 15- 30-m radio telescope operating at observing frequencies up to 43 GHz, with the lowest possible system temperatures on-board the spacecraft. To first order, this telescope can be thought of as an additional VLBA telescope in space, with enhanced sensitivity possible because of the lower system temperatures that can be achieved away from the Earth and its atmosphere.

Perhaps the single most important design parameter for ARISE is that routine observations must have a 7σ fringe-detection threshold of less than 10 mJy at all observing frequencies up to 22 GHz, in order to enable the observations of the classes of objects mentioned above. For a set of ground radio telescopes with fixed properties, the sensitivity depends on three basic parameters: (1) space telescope size and aperture efficiency (i. e., gain); (2) system noise temperature of the space telescope; and (3) sustainable data-acquisition rate of the ground and space observing systems. For one possible set of observing system parameters for ARISE, Table 2 compares the 22-GHz sensitivity of ARISE to that of VSOP at the same frequency, using a baseline to a 25-m VLBA telescope. For the ARISE mission in approximately 2005, it is assumed that the system temperatures of the VLBA antennas will be reduced from their current values by using lower noise receivers, while the sustainable bandwidth of the VLBA will be increased. The predicted nominal sensitivity of a baseline between two VLBA antennas in 2005 also is given for comparison.

Table 2. 22-GHz Sensitivity on Baseline to a Single VLBA Antenna

	VSOP	VLBA (2005)	ARISE
Diameter	8 m	25 m	30 m
Efficiency	40%	52%	60%
Sys. temp.	200 K	60 K	10 K
Data rate	128 Mb/s	1024 Mb/s	1024 Mb/s
7σ limit	450 mJy	20 mJy	6 mJy

The primary challenge in the design of ARISE is to develop a spacecraft whose performance is in the "Great Observatory" class exemplified by the Hubble Space Telescope and the Advanced X-ray Astrophysics Facility (AXAF), but whose cost is much more modest. This requires reliance on new technologies that are just maturing, without which design of such a mission would be prohibitively expensive. It also requires a careful consideration of the primary science goals from the beginning, so that the mission concept can be tailored to those specific goals. Tradeoffs can be made among the different observing-system parameters for ARISE that are listed in Table 2, but the scientific requirement of a routine 10-mJy detection threshold is quite important and should be maintained.

Several other requirements beyond the source-detection threshold are imposed on the ARISE mission by the scientific goals described above. These basic requirements are listed in Table 3, and discussed in more detail below.

Table 3. Basic requirements on ARISE

- 7σ sensitivity less than 10 mJy for all frequencies up to 22 GHz, with sensitivity of less than 5 mJy at 5 GHz highly desired
- Simultaneous dual polarization capability, with voltage isolation better than 3%
- Blind pointing to less than 0.1 beamwidths, or about 5 arcsec at 43 GHz
- Capability of slewing 1° (preferably 2°) and settling, with a blind pointing accuracy of 10 arcsec, in 60 seconds (preferably 15 seconds) or less
- Orbit determination accuracy of 5 10 cm

Antenna Design

A deployable antenna in the 20 30-m range, with high aperture efficiency at frequencies as high as 43 GHz is required for ARISE. This antenna must be reliable, inexpensive, and relatively low mass. The leading candidate for such an antenna, and the only one with a projected cost well below $100 million, is an inflatable antenna such as that currently being developed by L'Garde, Inc. In 1996, an experiment led by R. E. Freeland of the Jet Propulsion Laboratory and G. D. Bilyeu and G. R. Veal of L'Garde, Inc. will be performed in order to deploy a 14-m inflatable antenna structure in Earth orbit, with an on-orbit surface accuracy better than 1 mm r.m.s.[30,31] The inflatable antenna will be deployed from the Spartan experiment carrier released from the space shuttle, and its surface accuracy as a function of thermal characteristics will be measured by illuminating the off-axis paraboloidal sur-face with light-emitting diodes and measuring the reflectivity.

It is thought that the concept for the inflatable antenna can be extended in a straightforward manner to an antenna with a diameter as large as 30 meters. The total cost of the experiment to be performed in 1996 is only about $7 million, implying that a 30-m operational antenna could be built for roughly $25 million. Achievement of the 0.85 mm surface accuracy required for $\lambda/16$ performance at 22 GHz seems a reasonable expectation, while the 0.43-mm surface needed for similar performance at 43 GHz will be a greater challenge. The proposed orbit for ARISE will pass through the Earth's radiation belts, so charging and electrostatic discharge of the canopy of the inflatable antenna is a concern. Two possible solutions are electrical isolation of the antenna surface from the rest of the spacecraft or coating part of the canopy with conductive material; further study is needed to choose between these alternatives.

The current strawman design of ARISE would make use of an offset parabolic reflector, with the spacecraft bus located approximately at the prime focus of the large antenna. A conceptual picture of this situation is shown in Figure 1. This clear-aperture design will be beneficial in maximizing the aperture efficiency of the antenna and reducing the thermal coupling between the large antenna and the spacecraft systems. When more detailed design work is undertaken, other "optics" designs such as an on-axis, prime-focus system and different versions of Cassegrain systems will also be considered.

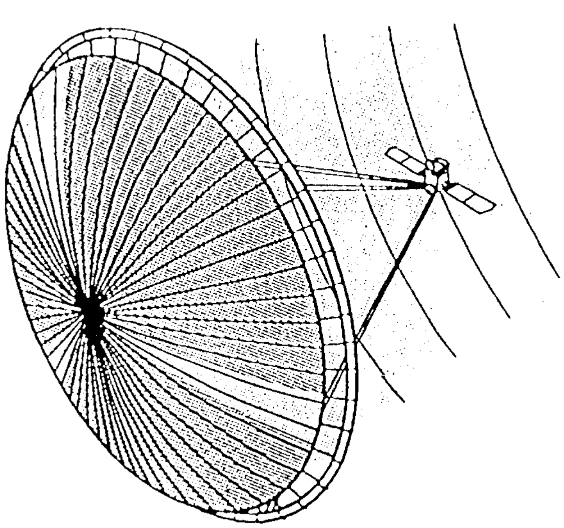

Figure 1. Conceptual design of ARISE spacecraft,

Low System Temperatures

The desired system temperatures in the range of 5-10 K at frequencies up to 22 GHz, and 20 K or less at 43 GHz, have not yet been obtained in a long-lifetime (3-5 years) space system. However, the space environment is a tremendous advantage in that the only real source of external noise will be the cosmic microwave background, since contributions from the Earth's atmosphere and ground pickup will be negligible. At ambient temperatures on the order of 18 K, amplifier noise temperatures of 10 K at 43 GHz and less than 10 K at 22 GHz have been measured, with future performance improvements expected.[32,33] Achievement of the desired total system temperature probably will require cooling the feed horns and may be aided by an off-axis (clear-aperture) antenna design. Two candidate technologies for achieving ambient receiver temperatures in the 15 K range are hydrogen-sorption coolers and passive cooling by evaporation of solid hydrogen.

Data Rate

The desired data rate for ARISE is in the range of 1-2 Gbit/s. The Mark IV VLBI system, currently being designed by Haystack Observatory and the European VLBI Network as a relatively inexpensive upgrade to the Mark III system that has been operational for 10 years, will be capable of recording and correlating data at rates up to 1 Gbit/s, with straightforward extension to 2 Gbit/s.[34,35] In addition, the recording systems at the VLBA telescopes already are capable of operating at 512 Mbit/s if two recorders are used simultaneously.[15]

The preferred downlink frequency for the/l)rmk ARISE mission will be in the Space Research band near 38 GHz. At this frequency, the 11-m antennas being built by NASA's Deep Space Network for support of VSOP and RadioAstron have about 30% aperture efficiency. Assuming ground receivers with system temperatures of 125 K and simple differential QPSK (Quadrature Phase Shift Keying) of the telemetry data, there will be a positive link margin of approximately 4 dB for a 0.5-111 spacecraft, antenna transmitting 10 Watts of power from a distance of 50,000 km. Modification of the ground antenna electronics to support a 38-GHz link and a 1-2 Gbit/s data rate would be required.

Orbit selection

The orbit for ARISE will have a perigee altitude of approximately 5,000 km, with an apogee altitude to be selected from a range of roughly 12,000 km to 50,000 km. The perigee altitude allows some overlap of ground-ground and ground-space baselines for calibration purposes, but keeps most of the orbit high enough so that the space-ground baselines provide information not available from ground-only VLBI. (Perigee altitudes closer to 10,000 km are not acceptable because of the imaging defects that would be caused by a lack of continuity between the ground-only and ground-space baselines.) An apogee altitude near 12,000 km would provide outstanding aperture-plane coverage, lending itself to very high dynamic range imaging, but would provide resolution only 2.5-3 times that achievable from the ground at the same wavelength. Much higher apogee altitudes will provide superior angular resolution at the expense of dynamic range in source images. An orbit with an inclination near 60° is preferred in order to minimize occultations and orbit precession, but such orbits have a considerable penalty in available science payload for a given launch vehicle. The final orbit can be selected only after a detailed tradeoff has been made between the scientific goals and spacecraft design; the selection should not be made until scientific results from VSOP and RadioAstron are available to help in making the tradeoffs.

Spacecraft Mass and Launch-Vehicle Capability

The expected mass of VSOP is 815 kg, including approximately 250 kg for the radio telescope.[13] There is no reason to expect that the mass of ARISE must be dramatically larger. The 14-m inflatable antenna structure that will be used for the 1996 shuttle experiment has a mass of 60 kg.[30] Therefore, the estimated mass of a 30-m version of the same type of antenna would be no more than about 300 kg. Provided the cryogenic systems do not contribute more than a few hundred kilograms, the total mass for ARISE should be considerably less than 1500 kg. An Atlas I launch vehicle is capable of delivering this mass to an orbit with an inclination in the range of 0° to 60° and an apogee altitude in the range of 12,000 to 50,000 km. A more detailed spacecraft design will be required to determine whether a Delta launch vehicle might be acceptable or if an Atlas II is necessary.

Orbit determination and phase referencing

Highly accurate orbit determination will be performed by means of two precision Global Positioning System (GPS) receivers on-board ARISE, one looking outward at the GPS satellites above the spacecraft and one looking down toward the satellites on the far side of the Earth.[36,37] Preliminary covariance analyses indicate that a 3-dimensional positional accuracy of 4 cm is possible for the reconstruction of the orbit at a 20,000-km altitude, while an accuracy of 10 cm is achievable for a 50,000-km altitude. These accuracies are essential for making water-maser distance measurements and for global astrometry for reference-frame unification.

The accurate orbit determination also will be important for the technique of phase referencing. This technique is used to extend the coherent integration times in order to detect interference fringes on sources much weaker than those that could be detected otherwise. The method involves alternating observations of a relatively strong VLBI source with a weaker program source on time scales of minutes.[38,39] Provided that the VLBI baseline is known very accurately, the interferometric phase found for the stronger source can be interpolated to estimate the phase for the weaker source, enabling coherent addition of many observation segments on the weaker source. This technique is critical for extending the detection threshold to yet weaker sources, such as some radio stars and Seyfert galaxies. Given the estimated density of VLBI reference sources and the predicted orbit-reconstruction accuracy for ARISE, it should be capable of phase referencing at 1.7 and 5 GHz in most cases, and possibly at 22 GHz. A phase reference capability at the lower frequencies will require a 1° slew every 2 minutes, with the total slew time (including settling) taking no more than 30 seconds. For phase referencing to be possible at 22 GHz, slews of up to 2° in distance would be required every 30 seconds, with the total slew time (including settling) taking no more than 15 seconds. Since such short, rapid slews and short settling times will be difficult for the ARISE configuration, the possibility of re-pointing the antenna 2° at 22 GHz by means of rotation of a small mirror also should be considered.

Attitude control requirements

The use of a large antenna at high frequencies, and the desire to make the rapid slews required by phase referencing, impose severe design constraints on the attitude-control system. Because most VLBI sources will not give an accurately measurable deflection in the total received power of the observing system, blind pointing is usually necessary. For accurate amplitude calibration, the electrical axis of the radio telescope must be pointed with an accuracy of about 0.1 beamwidths, corresponding to 5 arcsec for a 30-m antenna at 43 GHz, and 10 arcsec for the same antenna at 22 GHz. This pointing accuracy must be achieved over a wide range of Sun angles, from sources at about 30° from the Sun, to sources at right angles from the Sun (which will create the largest thermal gradients across the telescope) and those opposite the Sun. Pointing the spacecraft body alone is not sufficient, since the knowledge of the electrical axis of the radio telescope also is required. In order to minimize the time spent in changing sources, it is desirable for a 180° slew to be achieved in no more than 30 minutes.

It is anticipated that slews will be accomplished by using reaction wheels with large angular momentum capacities, since thrusters are not capable of providing the desired accuracy in a short time and would require enormous fuel stores. Since the spacecraft orbit is well within the Earth's magnetic field, the reaction wheels can be unloaded using magnetic torquers rather than with large thruster systems. The problem of moving a large antenna (albeit a relatively light one) at the end of a long moment arm without creating excessive torques in the struts connecting the spacecraft body to the antenna needs to be studied in detail. Fortunately, the inflatable antenna is intrinsically a highly damped structure, and it may be feasible to replace or strengthen the inflatable struts with small deployable truss structures.

Summary

This paper has described the wealth of scientific investigations that can be made with a high-sensitivity Space VLBI mission such as ARISE. These science goals make ARISE a worthy successor to the VSOP and RadioAstron experiments which will take place in the late 1990s. The basic design of the ARISE mission has been summarized in Table 4. Many of the design choices are still quite preliminary, and considerable additional work will be required to finalize these choices and provide more detailed spacecraft and mission designs. However, the technologies for the key observing elements, namely the large antenna and the space-qualified cryogenic systems, appear to be at hand and surprisingly affordable.

Table 4. Preliminary design parameters of ARISE

- Antenna: 20 30 meter diameter, off-axis/break paraboloid, inflatable strut.turc
- Receivers: 1.7, 5, 22, and 43 GHz, with system temperatures of 5- 20 K (increasing with increasing frequency)
- Polarization: Simultaneous dual circular polarization at 5 and 22 GHz
- Data rate: 1-2 Gbit/s, with channel bandwidths ranging from 1 to 16 MHz
- Perigee altitude: 5,000 km
- Apogee altitude: 12,000 50,000 km
- Orbit inclination: 60°
- Orbit determination: 2 on-board GPS receivers
- Blind-pointing accuracy: 5 arcsec
- Slew rate: 180°/30 minutes
- Phase-referencing slews: 1°- 2° in 15 60 seconds
- Attitude control: reaction wheels, unloaded by magnetic torquers

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